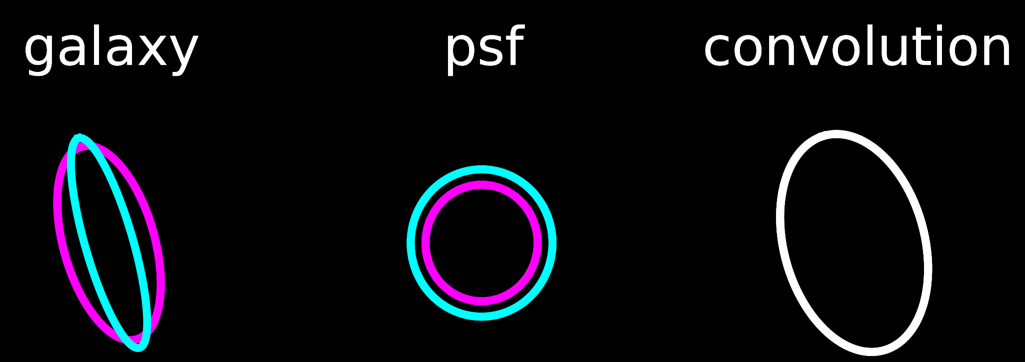
The atmosphere and chromatic PSF effects on galaxy shape measurement

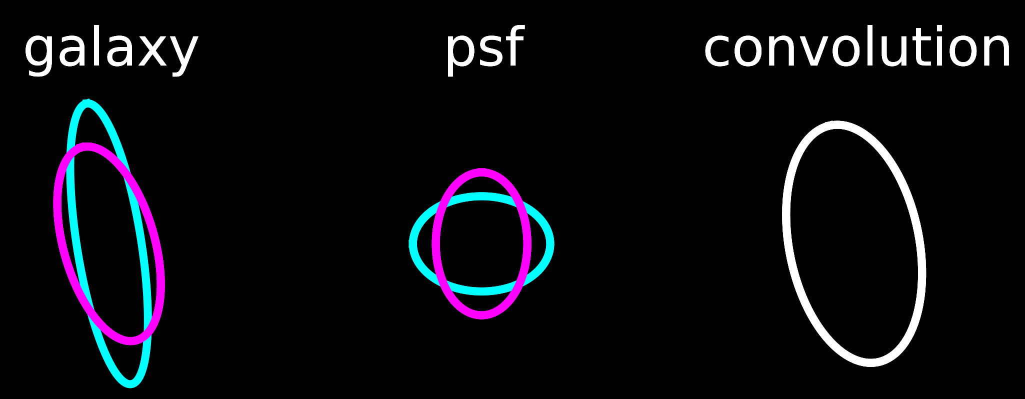
Joshua Meyers

PSF misestimation



True galaxy gets convolved with PSF;
makes observed galaxy shape bigger and (generally) rounder.

Shape measurement software attempts to invert this transformation.

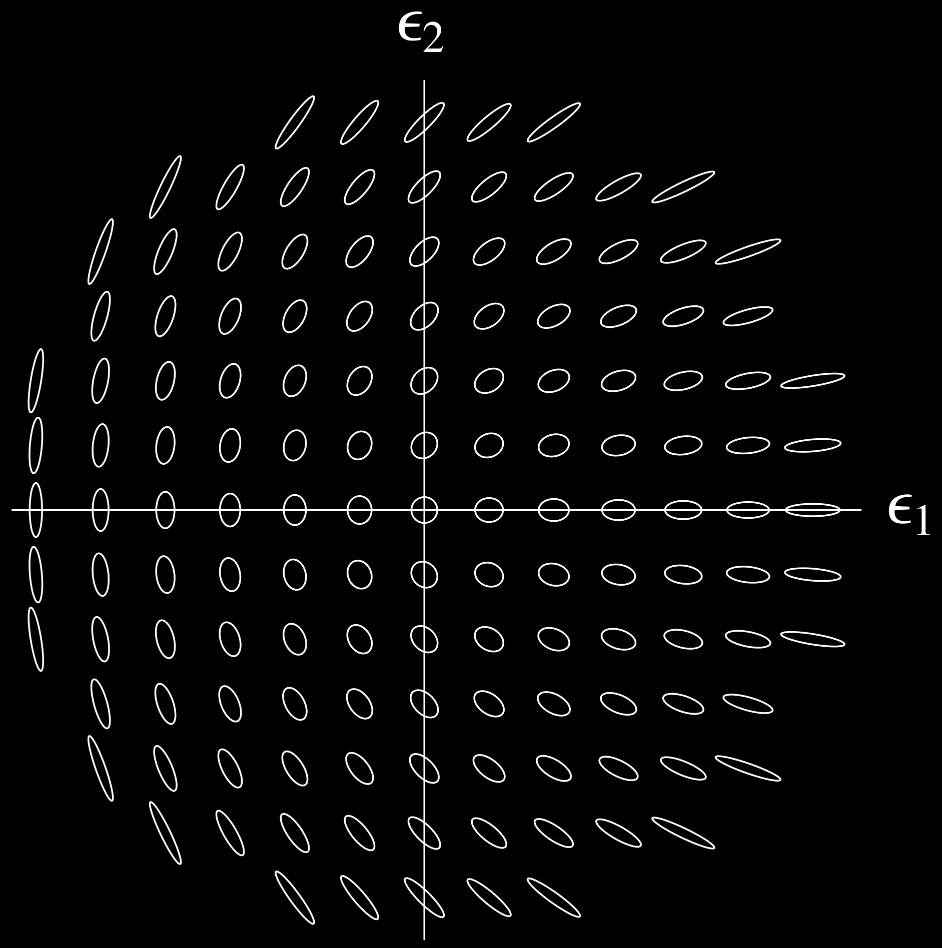


Misestimating PSF size or shape leads to biased galaxy shape inferences.

PSF parameter definitions

Second moments: $$I_{\mu\nu} = \frac{1}{\mathrm{flux}} \int I(x,y)(\mu - \bar{\mu})(\nu - \bar{\nu})\, \mathrm{d}x\, \mathrm{d}y$$

Ellipticities: $$\epsilon_1 = \frac{I_{xx} - I_{yy}}{I_{xx} + I_{yy}} \quad \epsilon_2 = \frac{2I_{xy}}{I_{xx} + I_{yy}}$$



Second-moment squared radius: $$r^2 = I_{xx} + I_{yy}$$

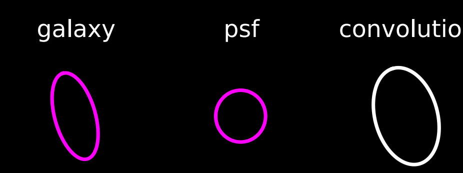
From ellipticity to shear: $$\langle \epsilon \rangle \approx 2\gamma$$

Characterizing shear biases: $$\hat{\gamma}_i = \gamma_i(1 + m_i) + c_i$$

PSF misestimation

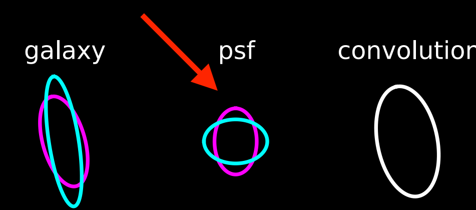
Second moments add under convolution:

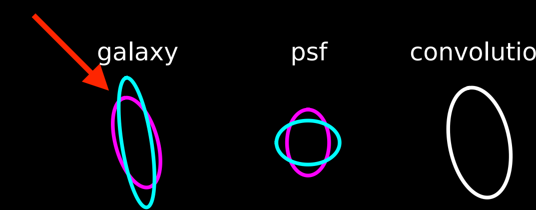
$$I^{\mathrm{obs}} = I^{\mathrm{gal}} + I^{\mathrm{psf}}$$



PSF misestimate

$$\Delta I^{\mathrm{psf}} = I^{\hat{\mathrm{psf}}} - I^{\mathrm{psf}}$$





Propagate into ellipticity

$$\epsilon_1 \rightarrow \frac{(I^{\mathrm{gal}}_{xx} + \Delta I^{\mathrm{psf}}_{xx}) - (I^{\mathrm{gal}}_{yy} + \Delta I^{\mathrm{psf}}_{yy})}{(I^{\mathrm{gal}}_{xx} + \Delta I^{\mathrm{psf}}_{xx}) + (I^{\mathrm{gal}}_{yy} + \Delta I^{\mathrm{psf}}_{yy})} \qquad \epsilon_2 \rightarrow \frac{2(I^{\mathrm{gal}}_{xy} + \Delta I^{\mathrm{psf}}_{xy})}{(I^{\mathrm{gal}}_{xx} + \Delta I^{\mathrm{gal}}_{xx}) + (I^{\mathrm{gal}}_{yy} + \Delta I^{\mathrm{gal}}_{yy})}$$

Algebra

$$\epsilon_1 \rightarrow \epsilon_1 \underbrace{\left(1 - \frac{\Delta I^{\mathrm{psf}}_{xx} + \Delta I^{\mathrm{psf}}_{yy}}{r^2_{\mathrm{gal}}}\right)}_{\mathbf{m}} + \underbrace{\frac{\Delta I^{\mathrm{psf}}_{xx} - \Delta I^{\mathrm{psf}}_{yy}}{r^2_{\mathrm{gal}}}}_{\mathbf{2c}} + \mathcal{O}\left(\Delta I\right)^2$$

$$\hat{\gamma}_i = \gamma_i(1 + m_i) + c_i$$

$$\epsilon_2 \rightarrow \epsilon_2 \overbrace{\left(1 - \frac{\Delta I^{\mathrm{psf}}_{xx} + \Delta I^{\mathrm{psf}}_{yy}}{r^2_{\mathrm{gal}}}\right)} + \overbrace{\frac{2\Delta I^{\mathrm{psf}}_{xy}}{r^2_{\mathrm{gal}}}} + \mathcal{O}\left(\Delta I\right)^2$$

generic, but assumes
unweighted second moments

Estimated impact of PSF misestimation on cosmology

Shear estimator: $\hat{\gamma}_i = \gamma_i(1 + m_i) + c_i$

Correlation function: $\langle \hat{\gamma}\hat{\gamma} \rangle_\theta = \langle \gamma\gamma \rangle_\theta (1 + 2\langle m \rangle) + \langle cc \rangle_\theta$

rough LSST requirements

$$m_{\mathrm{max}} \approx 0.003$$

$$c^2_{\mathrm{max}} \approx \sigma^2_{\mathrm{sys,max}} \approx 10^{-7}$$

Some sources of PSF misestimation

- Interpolation of atmospheric turbulence
  - Measure PSF at star positions, apply at galaxy positions
- Chromatic effects
  - PSF depends on wavelength
  - Measure PSFs from stars with stellar SEDs.
  - But PSF affecting galaxy is derived from a galactic SED.

(won't touch here, but same math applies…)

- sensor effects (tree rings, chip edges, brighter-fatter)
- image misregistration

The PSF depends on wavelength!

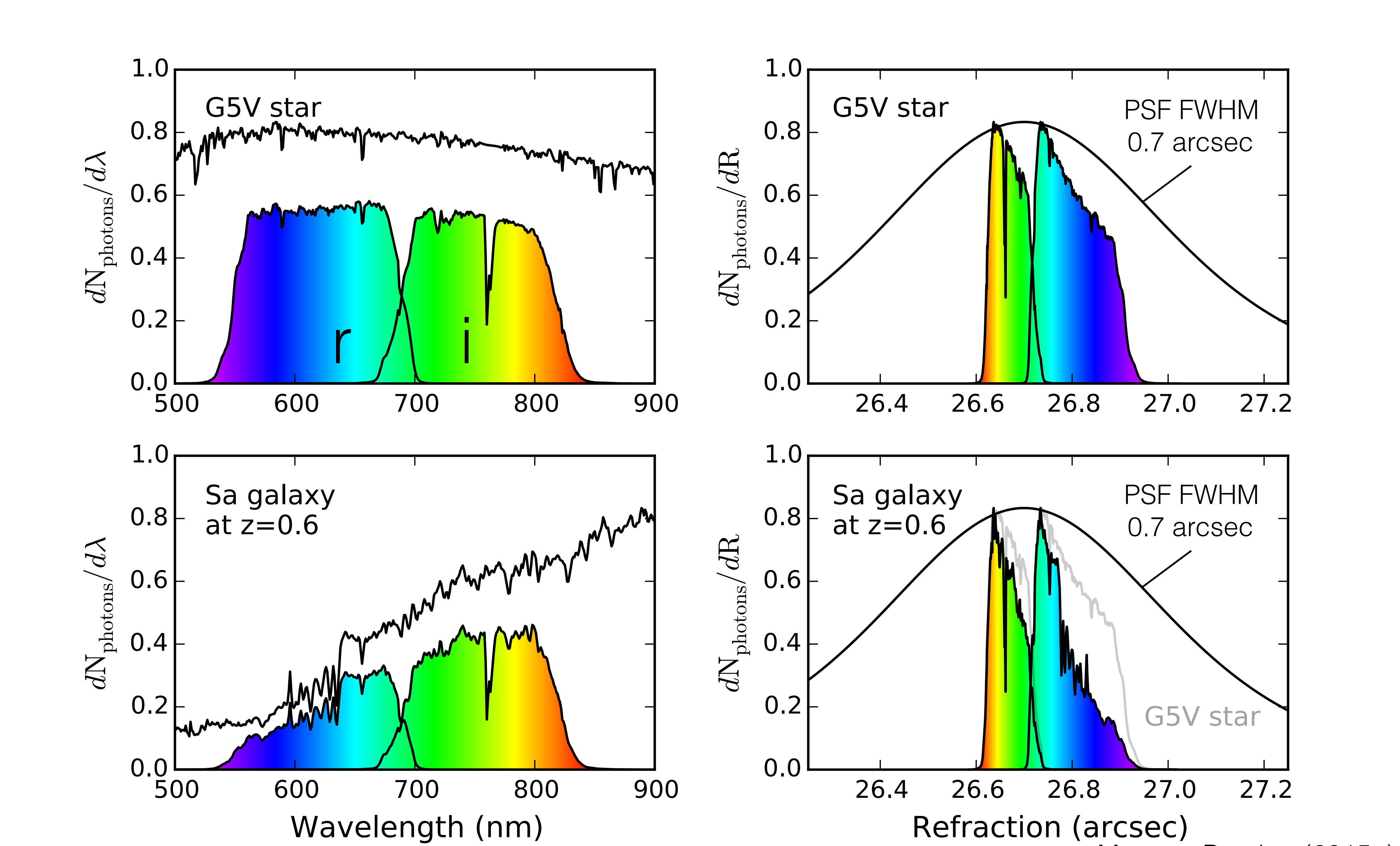
Some chromatic effects

- Optics - refraction, diffraction, aberrations — Cypriano++(2010), Voigt++(2012), Semboloni++(2013), Meyers+Burchat(2014)
- Sensors - absorption length of silicon — Meyers+Burchat(2015b)
- Chromatic seeing — Meyers+Burchat(2015a)
- Differential chromatic refraction (DCR) — Plazas+Bernstein(2012), Meyers+Burchat(2015a)

Differential chromatic refraction

Bluer photons refract more than redder photons when entering the Earth's atmosphere.

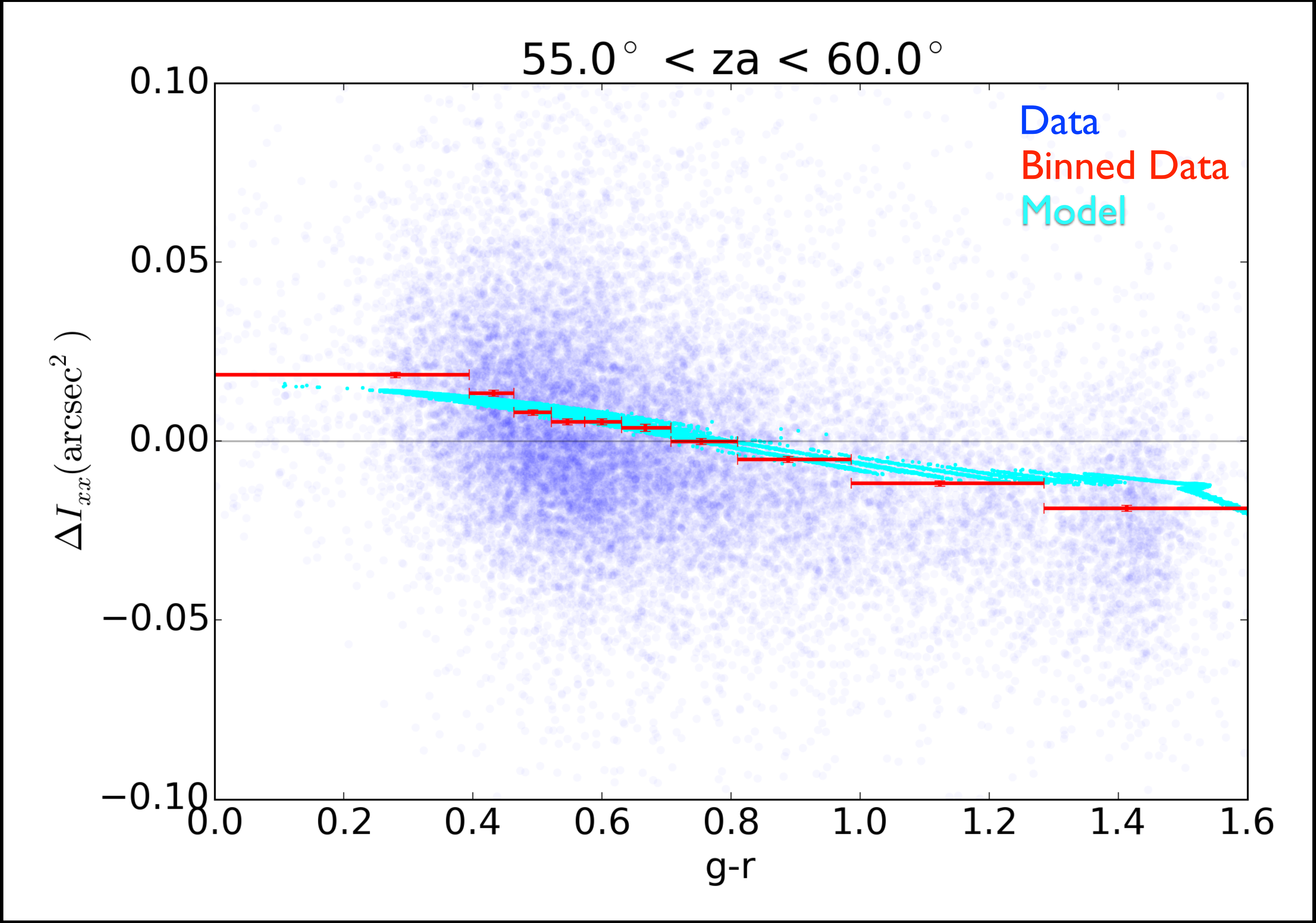
Zenith angle of 35°



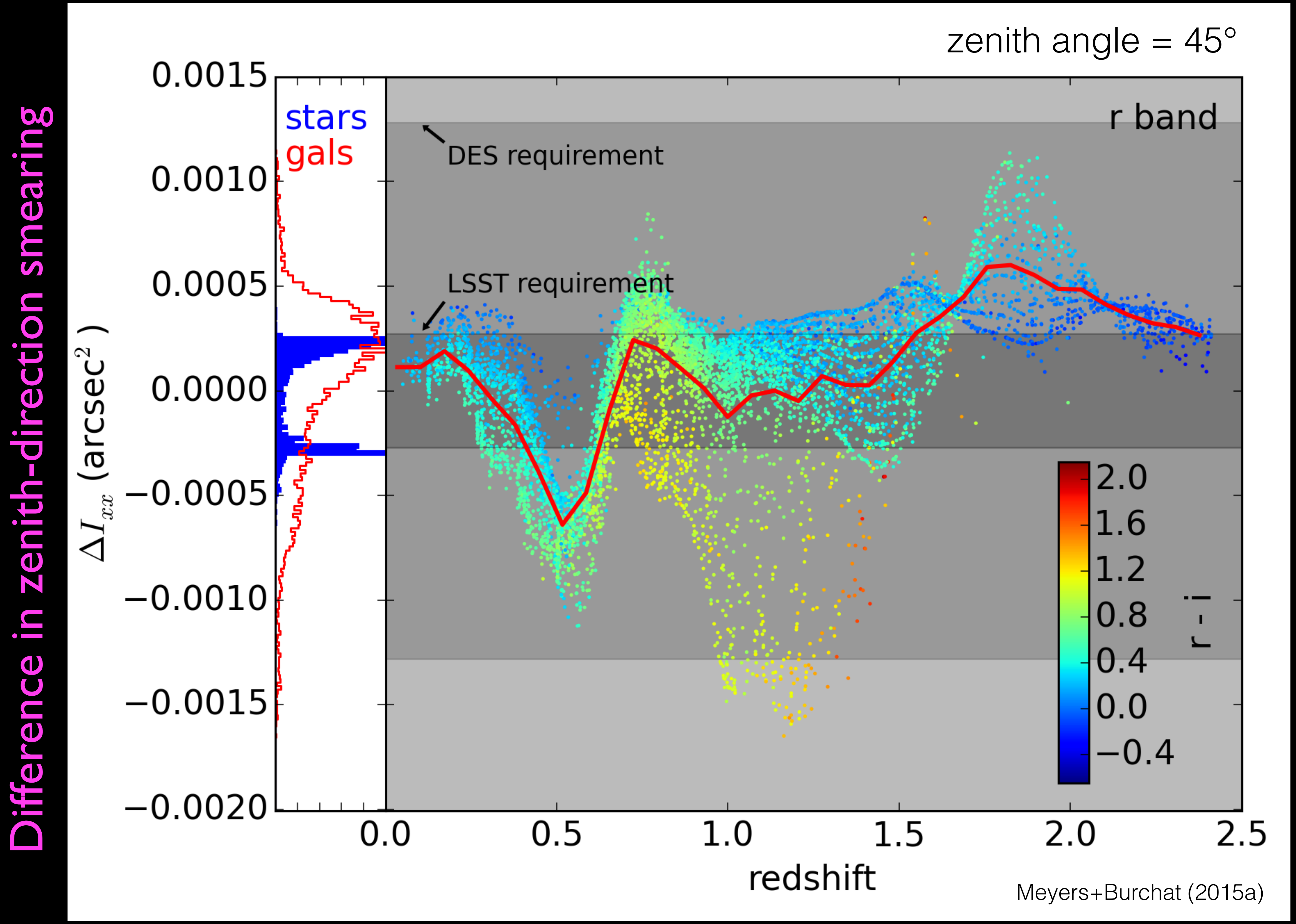
Meyers+Burchat (2015a)

Differential chromatic refraction - SDSS data

SDSS g-band zenith-direction second moment residuals.



LSST DCR requirements

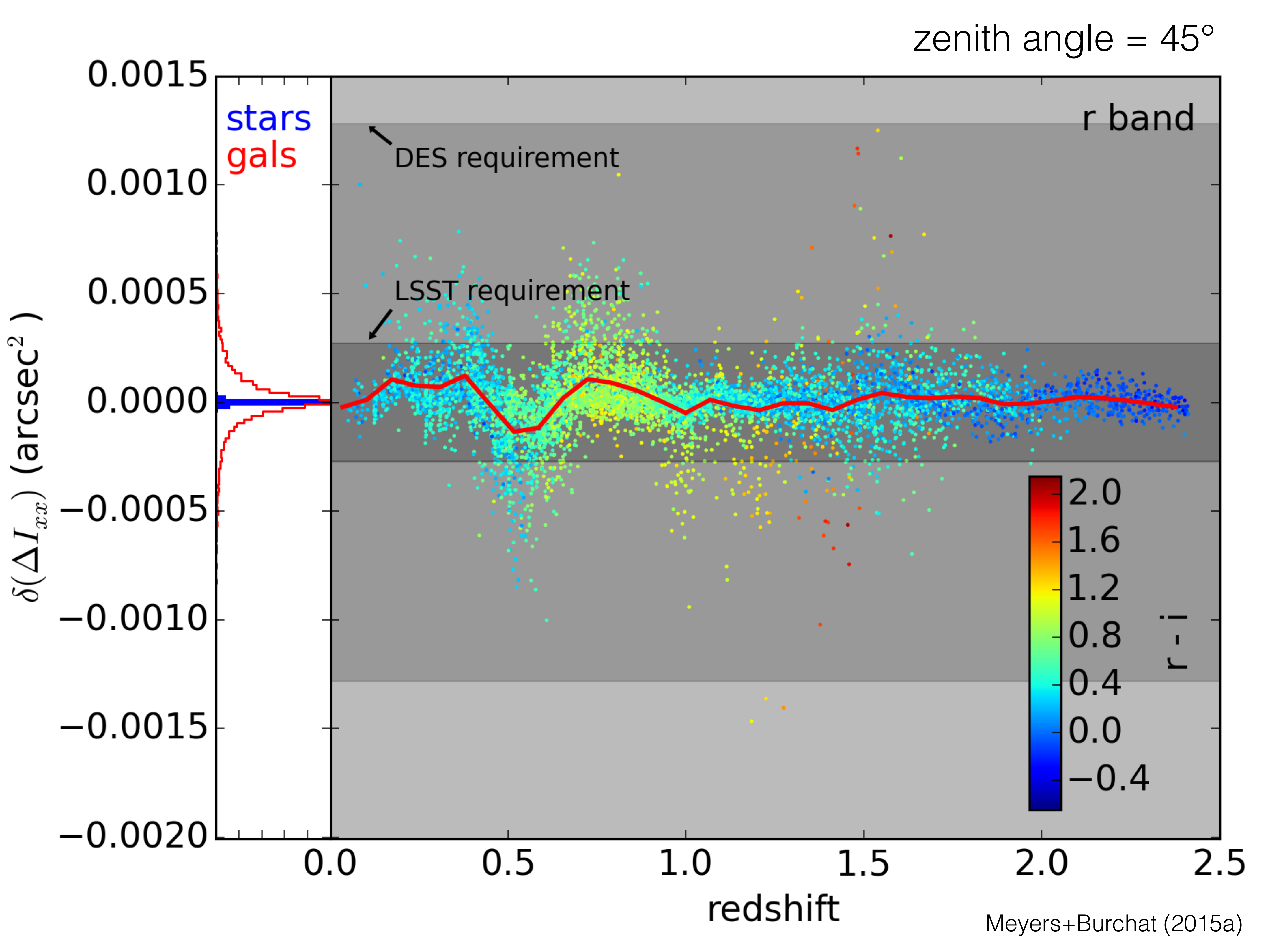


Corrections: learn SED from photometry

- Can correct if you know
  - PSF(λ)
  - The SED
- Train a machine-learning algorithm to predict chromatic bias as a function of photometry.
- Conceptually similar to a photometric redshift.

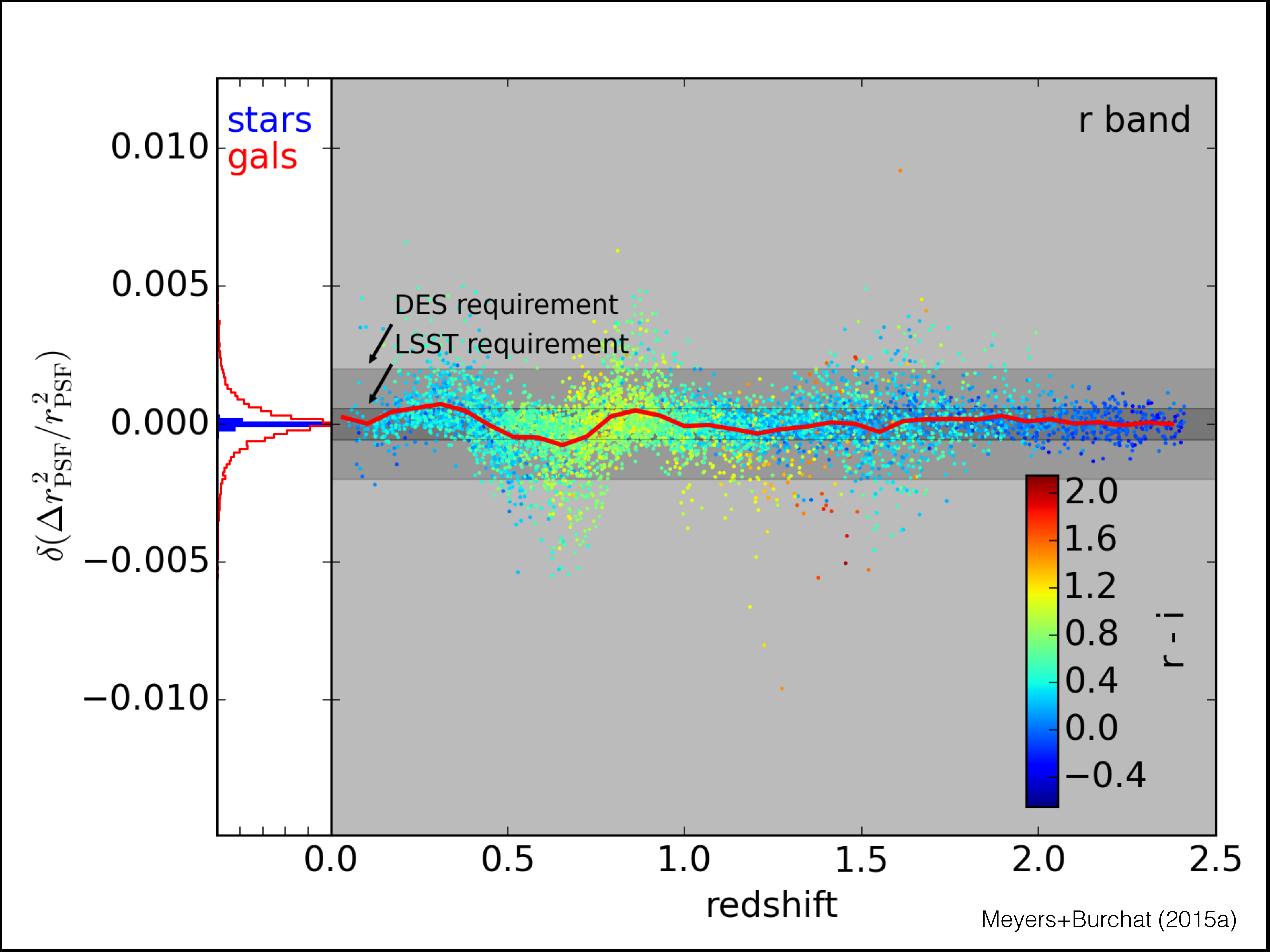
LSST DCR requirements

Difference in zenith-direction smearing

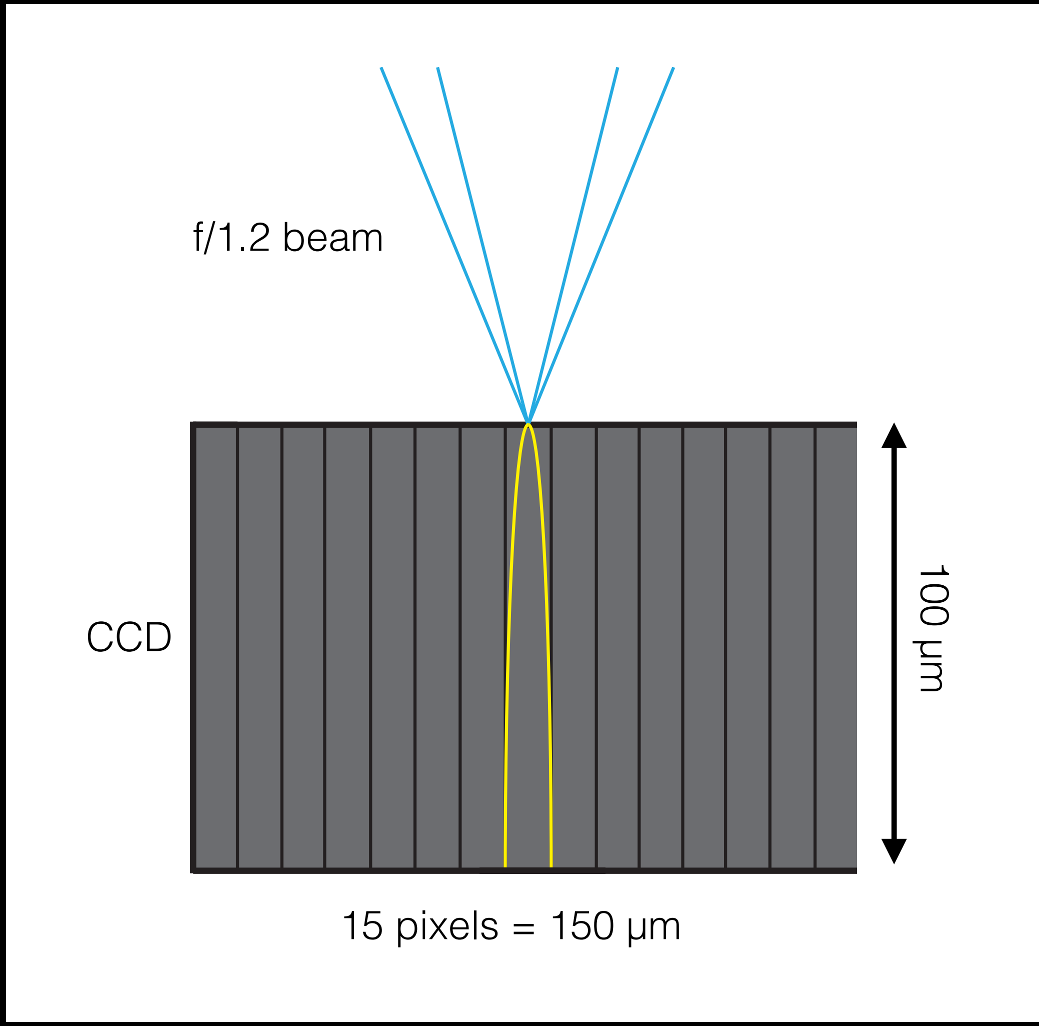


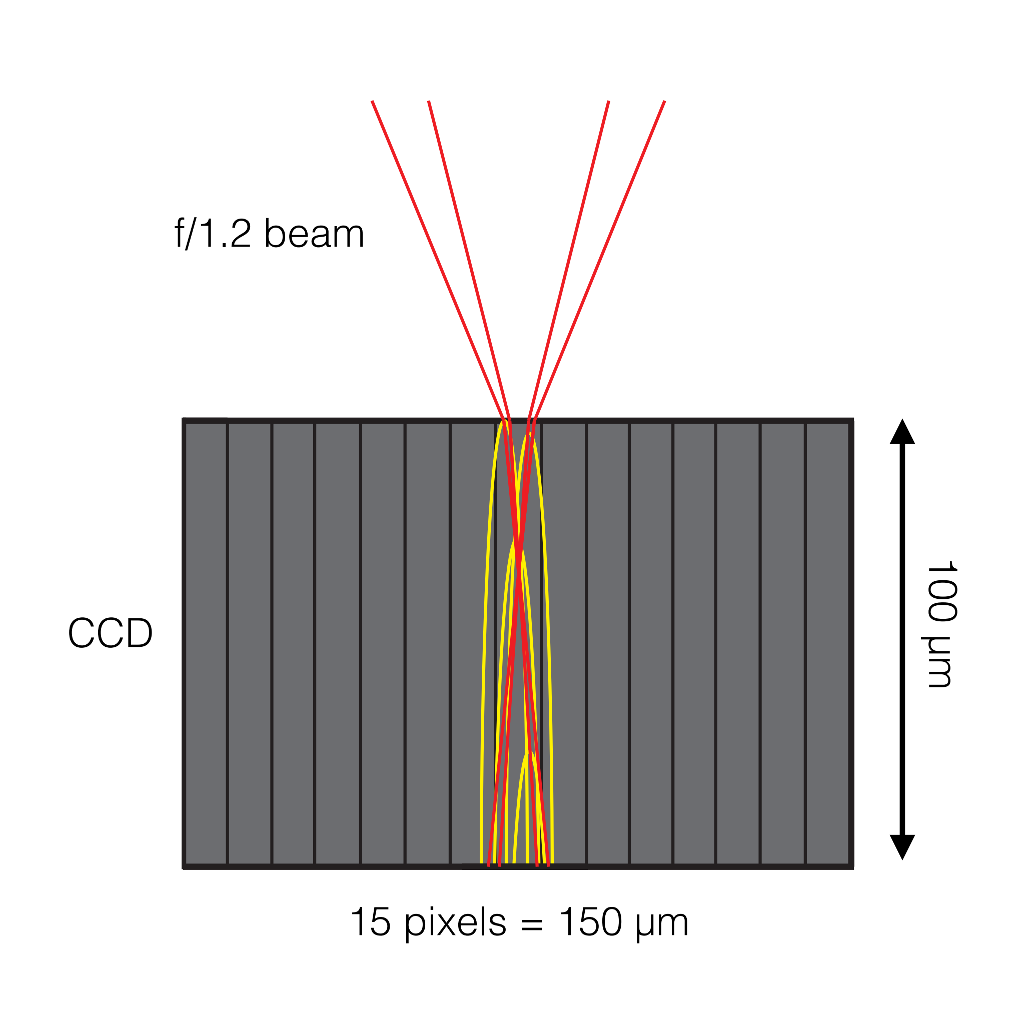
Chromatic Seeing Requirements - $\sigma(\lambda) \propto \lambda^{-1/5}$

Difference in PSF size



Fast beam and chromatic absorption length

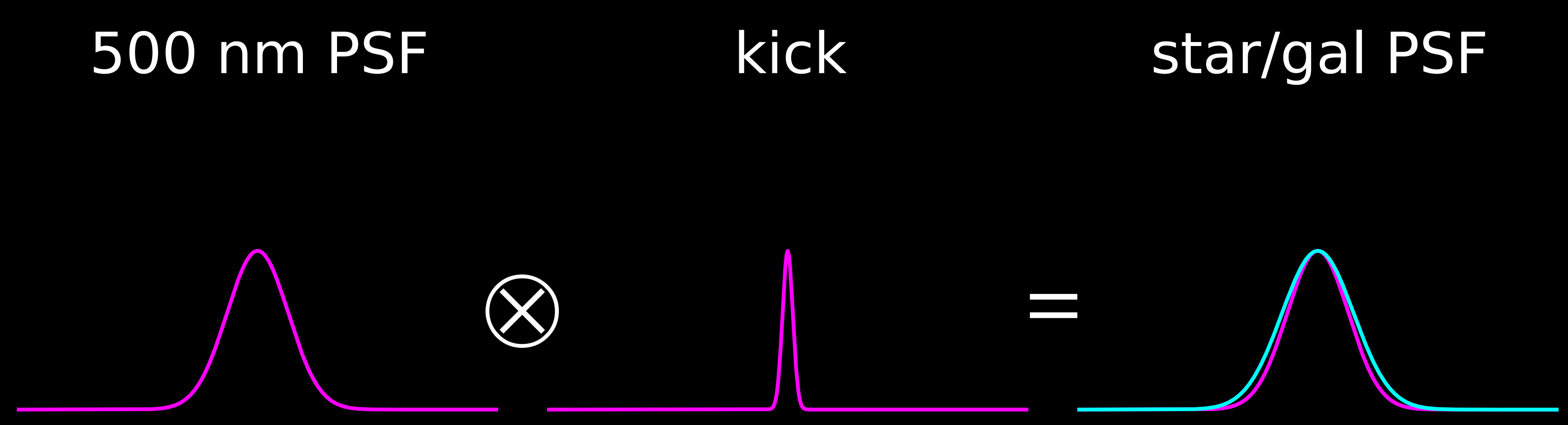




- LSST photons have significant transverse momentum inside silicon CCDs.
- Wavelength-dependent differences in conversion depth lead to differences in transverse conversion position.

Correct the catalog, or correct the PSF?

- Machine learning gives PSF bias; still need to correct galaxy shape.
- Correction depends on galaxy profile, airmass, seeing, focal plane position, …
- PSF-level correction before galaxy shape measurement may be easier for LSST.
- Dilate or convolve PSF by Gaussian kernel to restore correct 2nd moments reduces shape biases for LSST by factor of ~20.



Color gradients

- SED varies with position in real galaxies; so does the PSF.
- Voigt++12 and Semboloni++13 investigated this effect for Euclid, using simulated bulge+disk galaxies. They find a systematic bias around the size of the expected statistical uncertainties.
- Bias due to color gradient scales like

$$\frac{\mathrm{dPSF}}{\mathrm{d}\lambda} \times (\mathrm{filter\ width})^2 \times \frac{\mathrm{PSF\ area}}{\mathrm{gal\ area}}$$

- LSST/Euclid ~ (0.3) x $(0.4)^2$ x 3^2 ~ 0.4 (see Sowmya Kamath's poster!)
- However, real galaxies are not bulge+disk! Especially at high redshift. (See my poster!)

NGC 2442

PSF interpolation and the atmosphere

- Measure PSFs at positions of stars, interpolate to the position of galaxies.

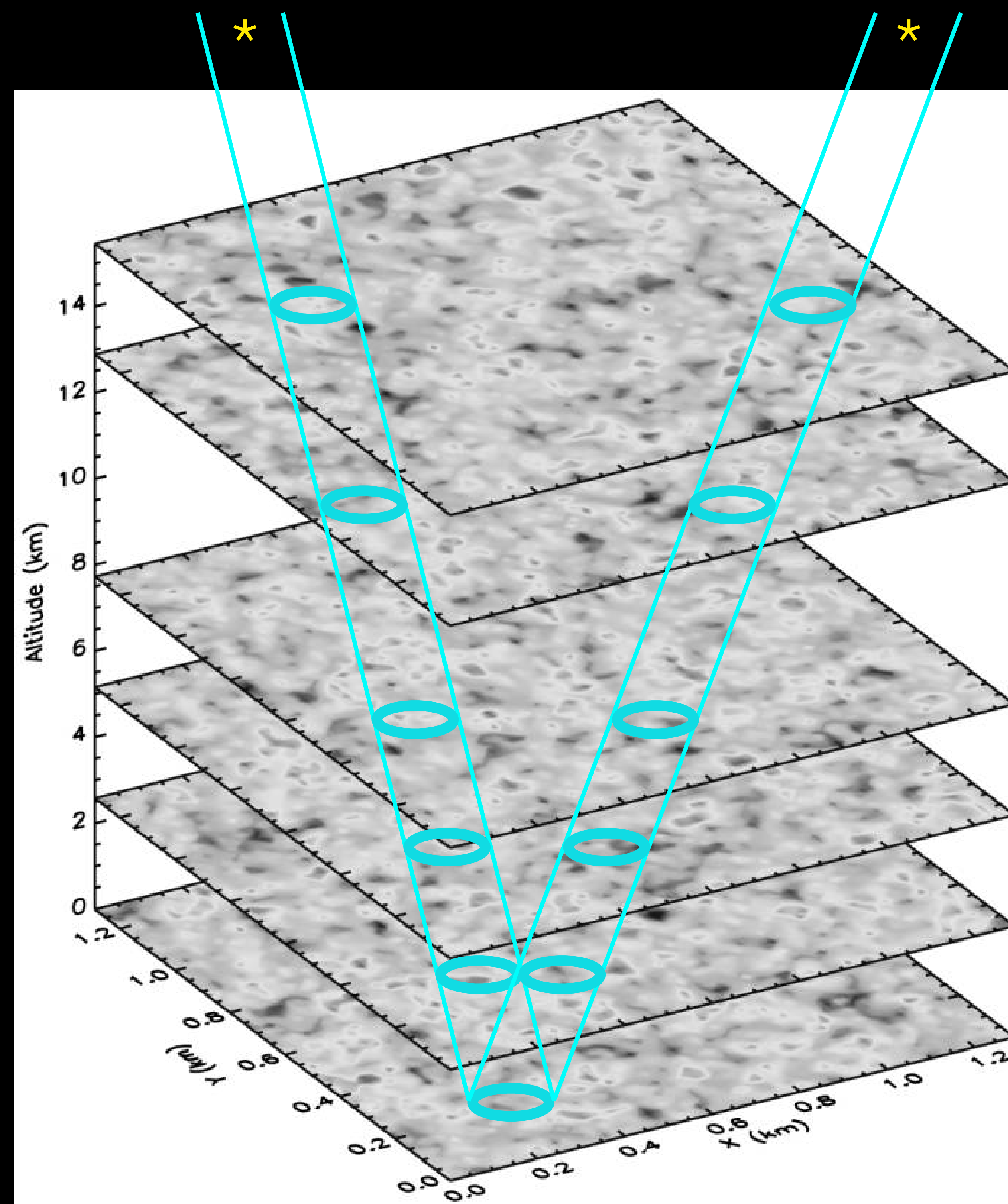
- Turbulence in atmosphere generates spectrum of refractive index variations, which in turn generate optical path differences.

$$\Psi(\nu) = 0.023 r_0^{-5/3} \left(\nu^2 + \frac{1}{L_0^2}\right)^{-11/6}$$

Fried parameter:
~ 10 - 20 cm

Outer scale:
~25 m

- Wind introduces spatial correlations in PSFs. Different angles see the same phase screen at slightly different times.

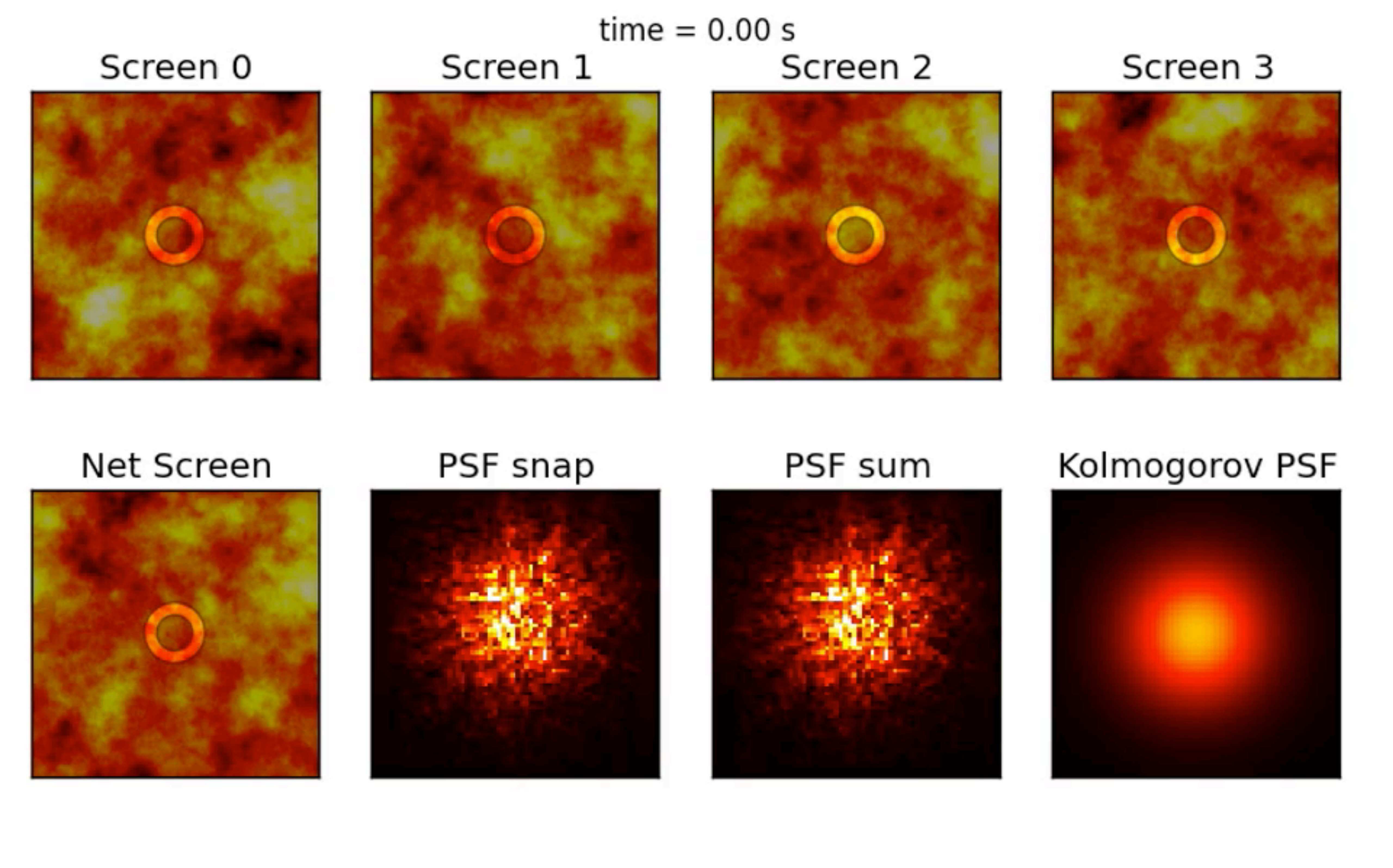


Jee+Tyson11

Instantaneous PSF

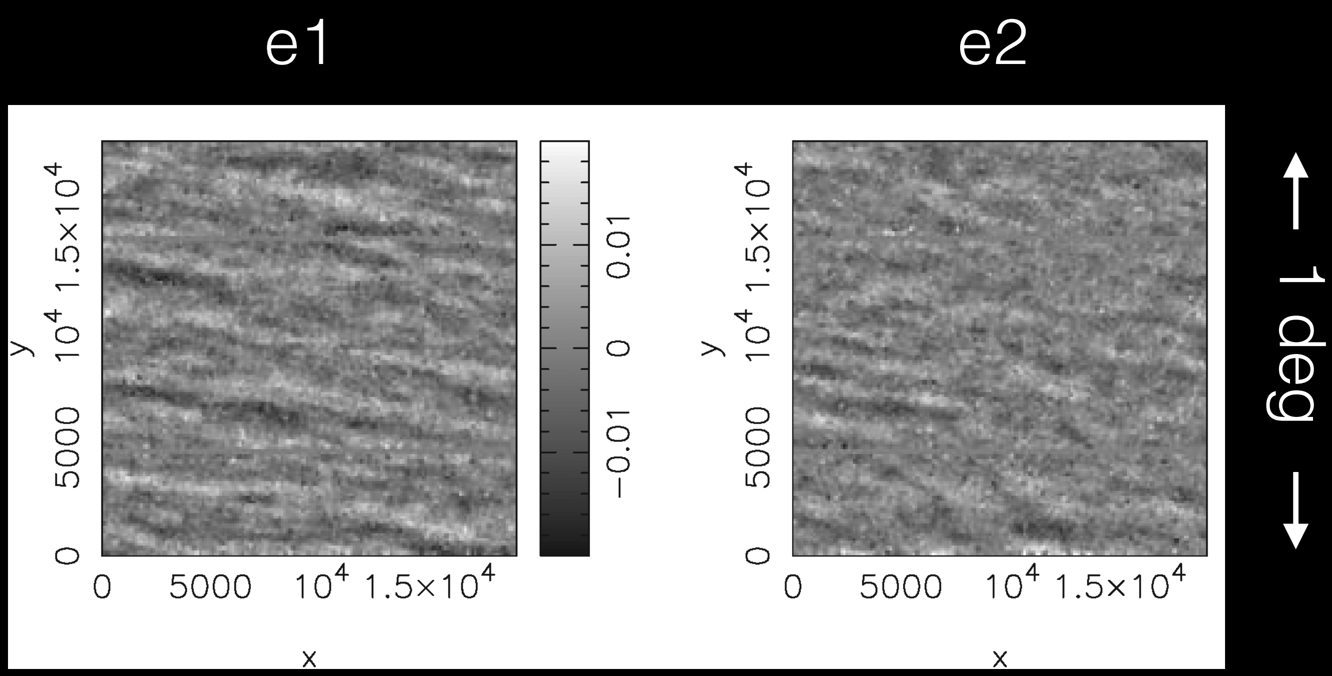
$$\mathrm{PSF} = \left|\mathcal{F}\{A(\rho,\phi)\exp(i\Phi(\rho,\phi))\}\right|^2$$

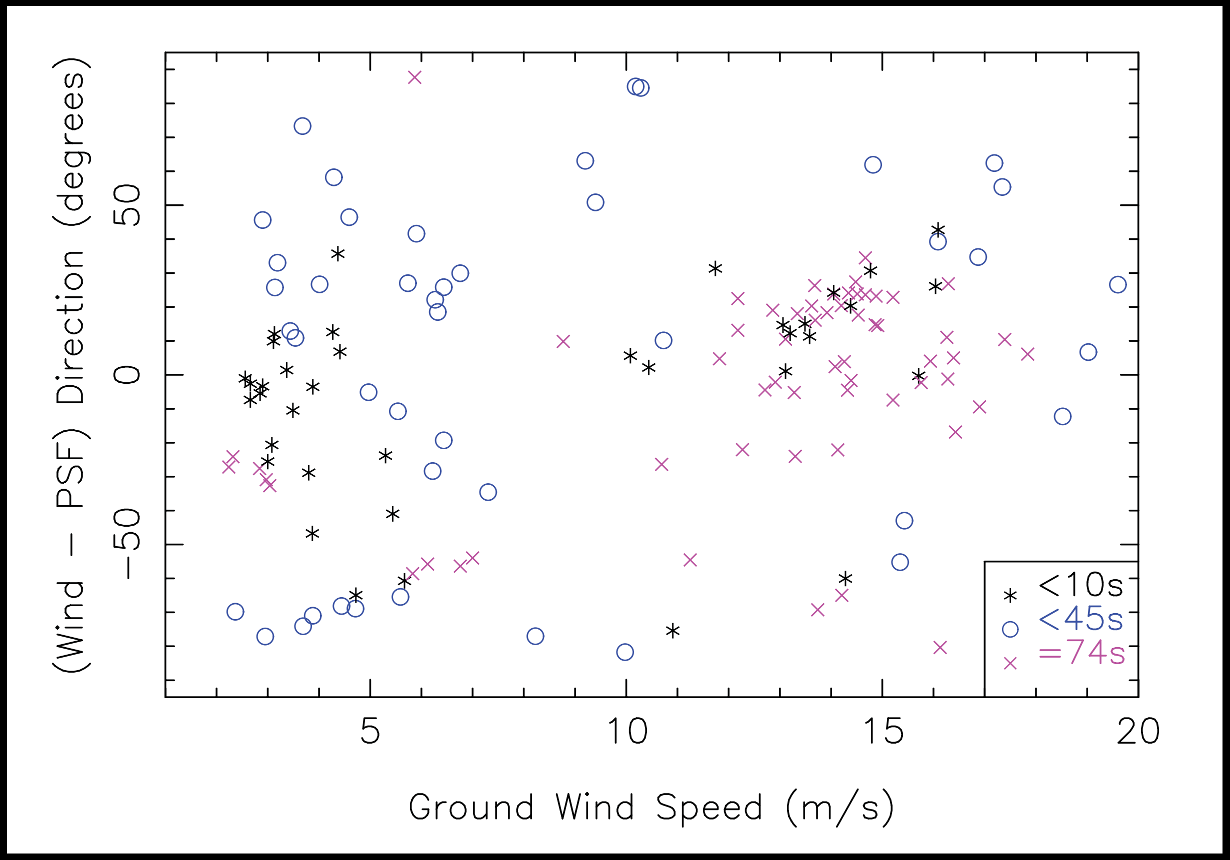
Atmosphere in motion

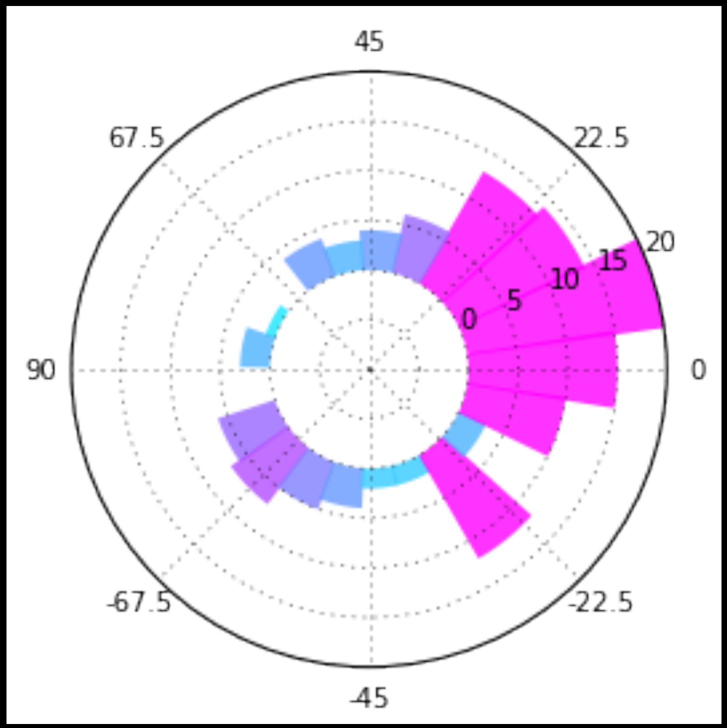


Heymans++12

- Studied PSF ellipticity in short exposures at CFHT.
- Atmospheric PSF has high frequency spatial correlations.
- Ellipticity correlation function amplitude scales like $t^{-1/2}$.
- Anisotropy not correlated with (ground) wind direction?

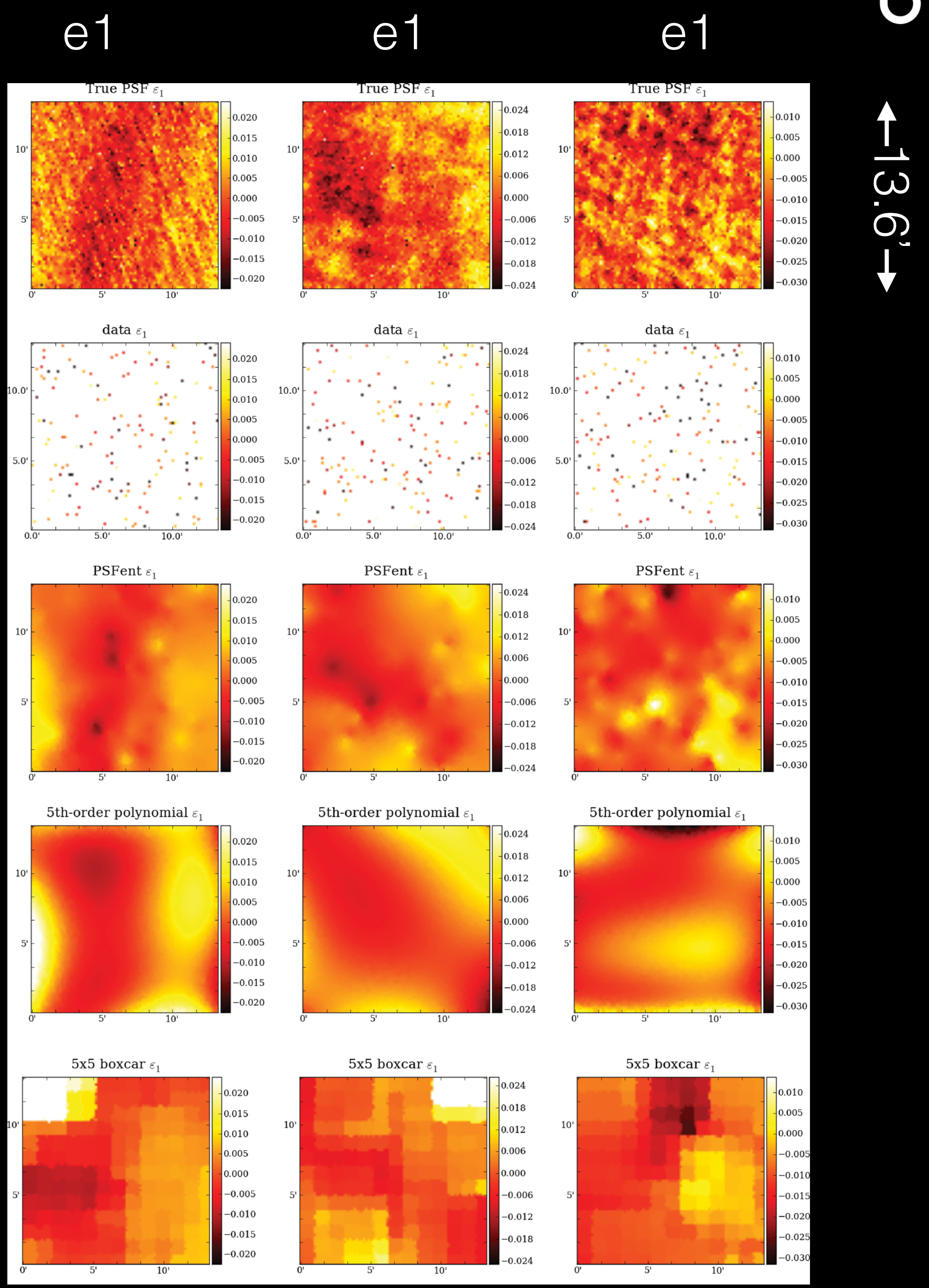






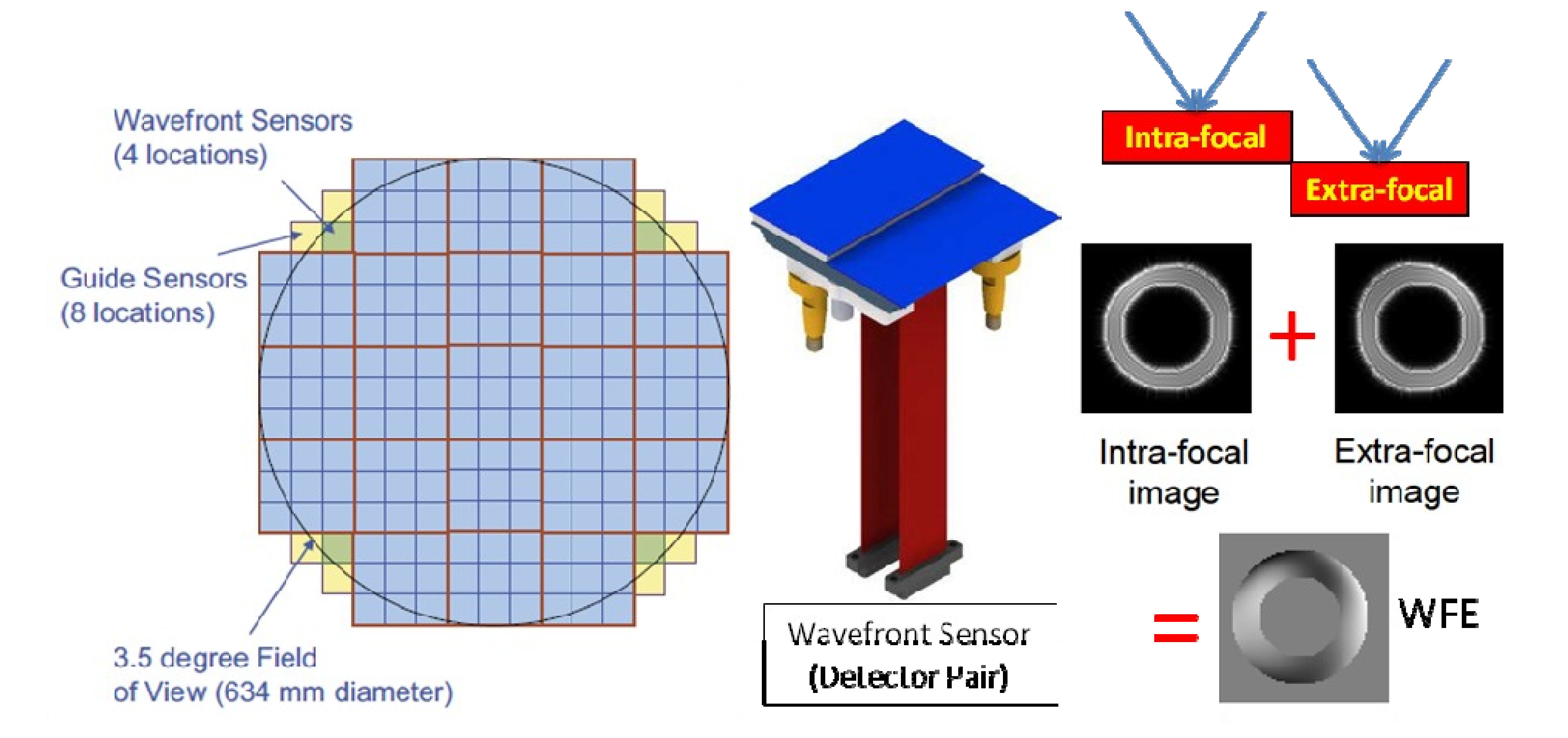
Chang++12

- Studied LSST PSF correlations using PhoSim.
- Chang++12 use a prior probability distribution to constrain the ellipticity and size variation on different scales.
- Tuned prior based on wide range of simulations.
- How can we use ancillary information to tune a prior for *specific* observations?
- Can a probabilistic approach make use of fainter stars?

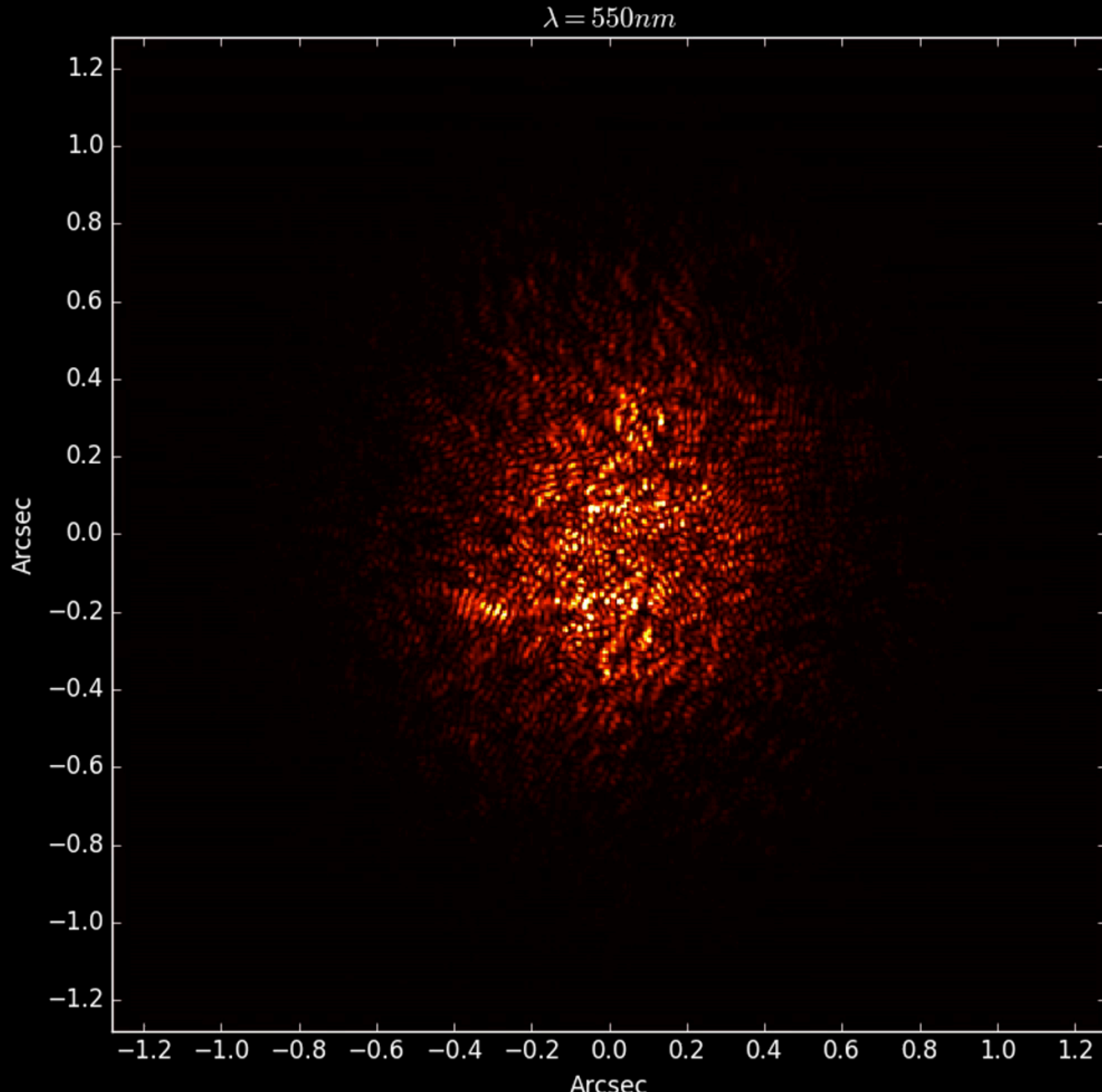


Corner rafts

- Can wavefront sensors usefully constrain ground layer turbulence? (given 15 sec integration times)
- Can scintillation on guide sensors (~10 Hz) provide useful constraints?

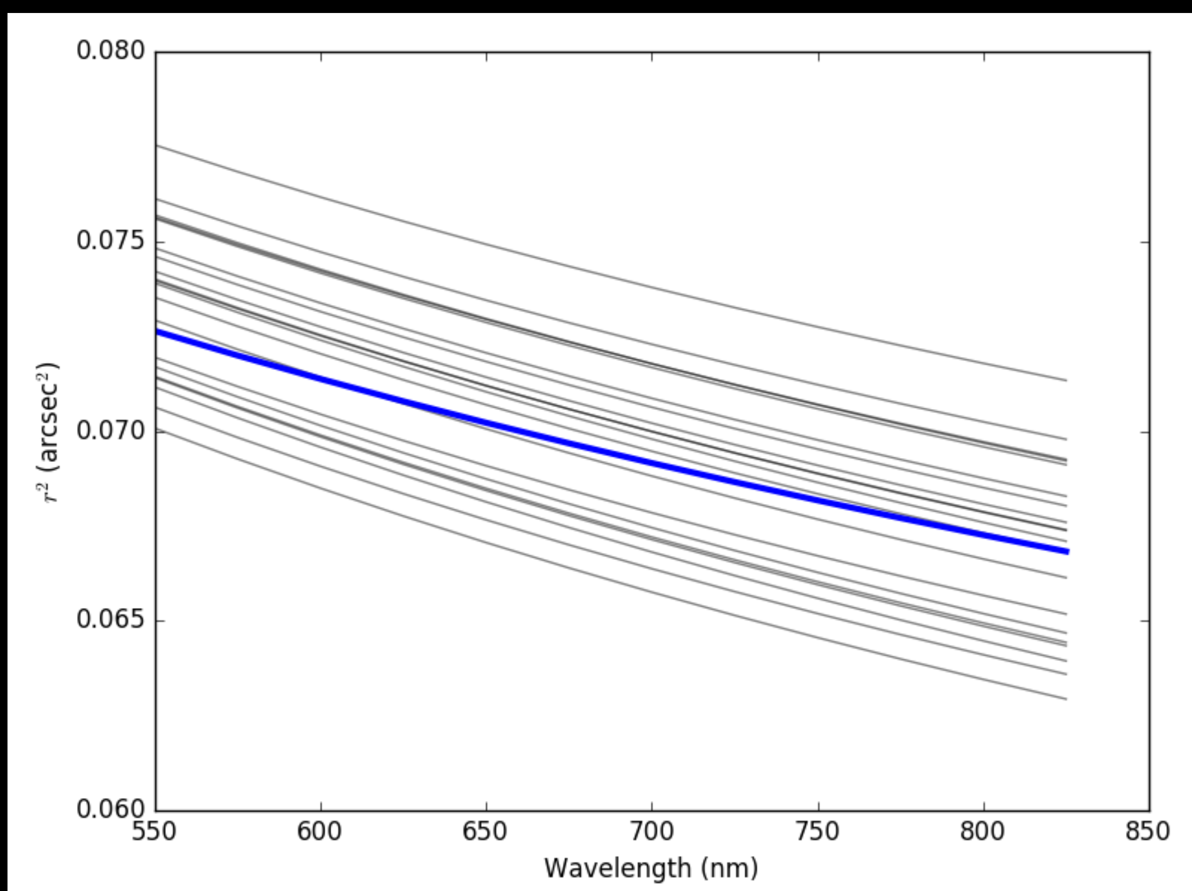


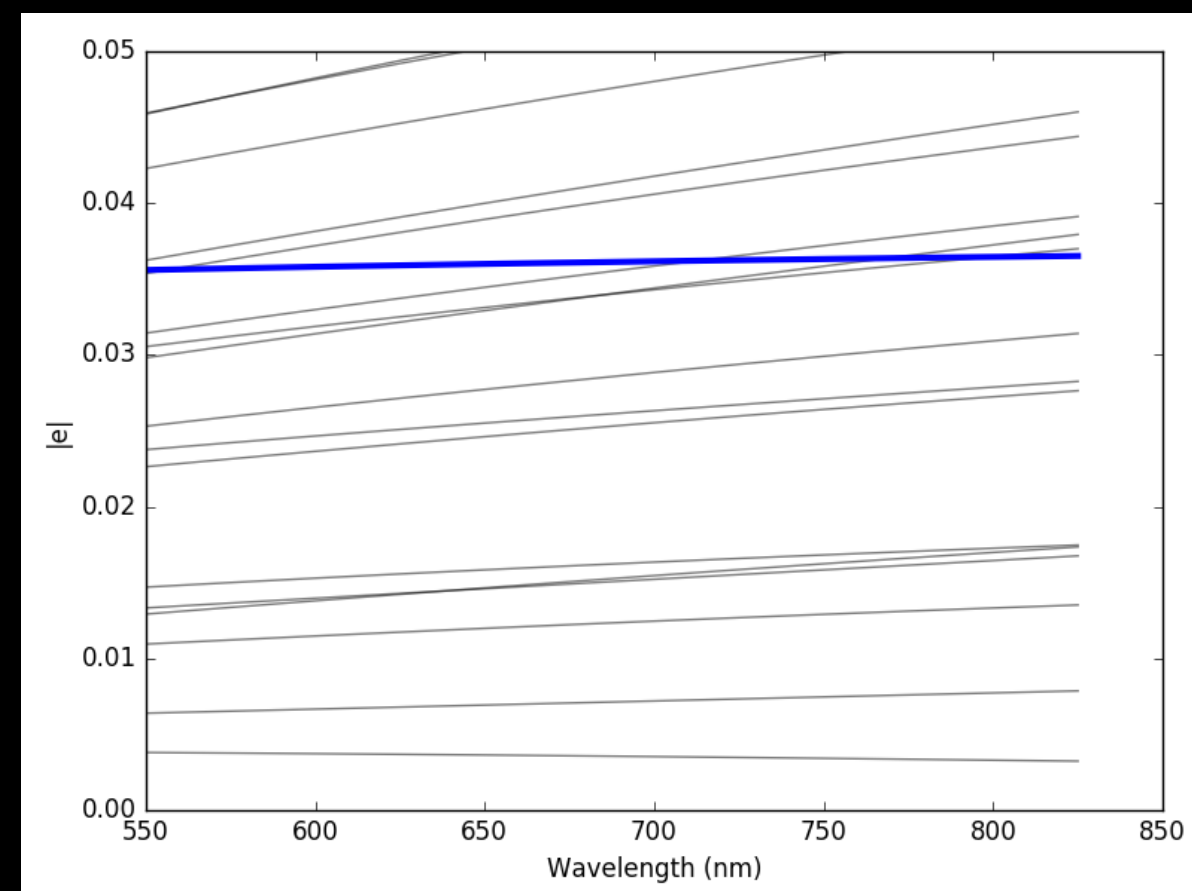
Chromaticity of atmospheric PSF?



Chromaticity of atmospheric PSF?

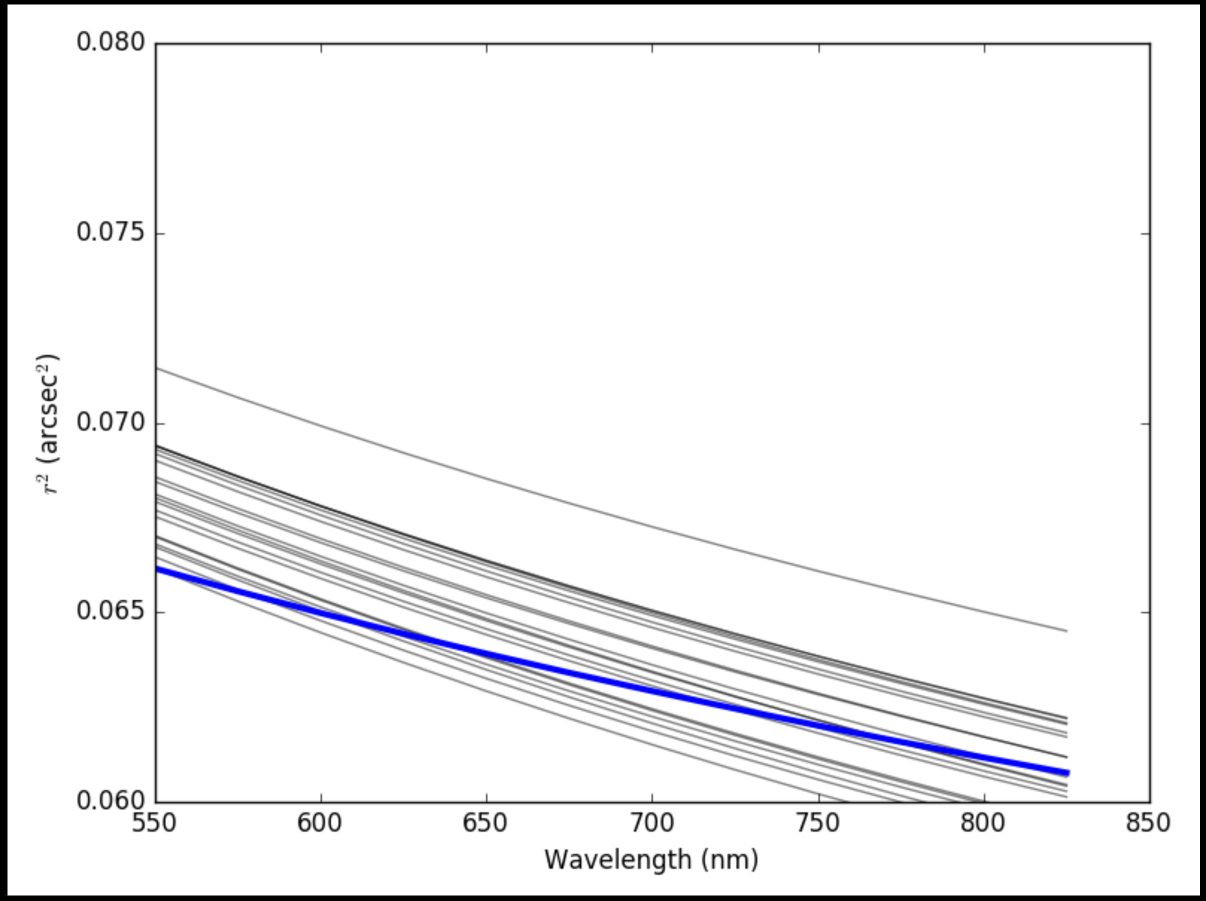
6 layers with Jee+Tyson relative amplitudes,
r0 = 0.2 m, L0 = infinity
20 atmosphere realizations

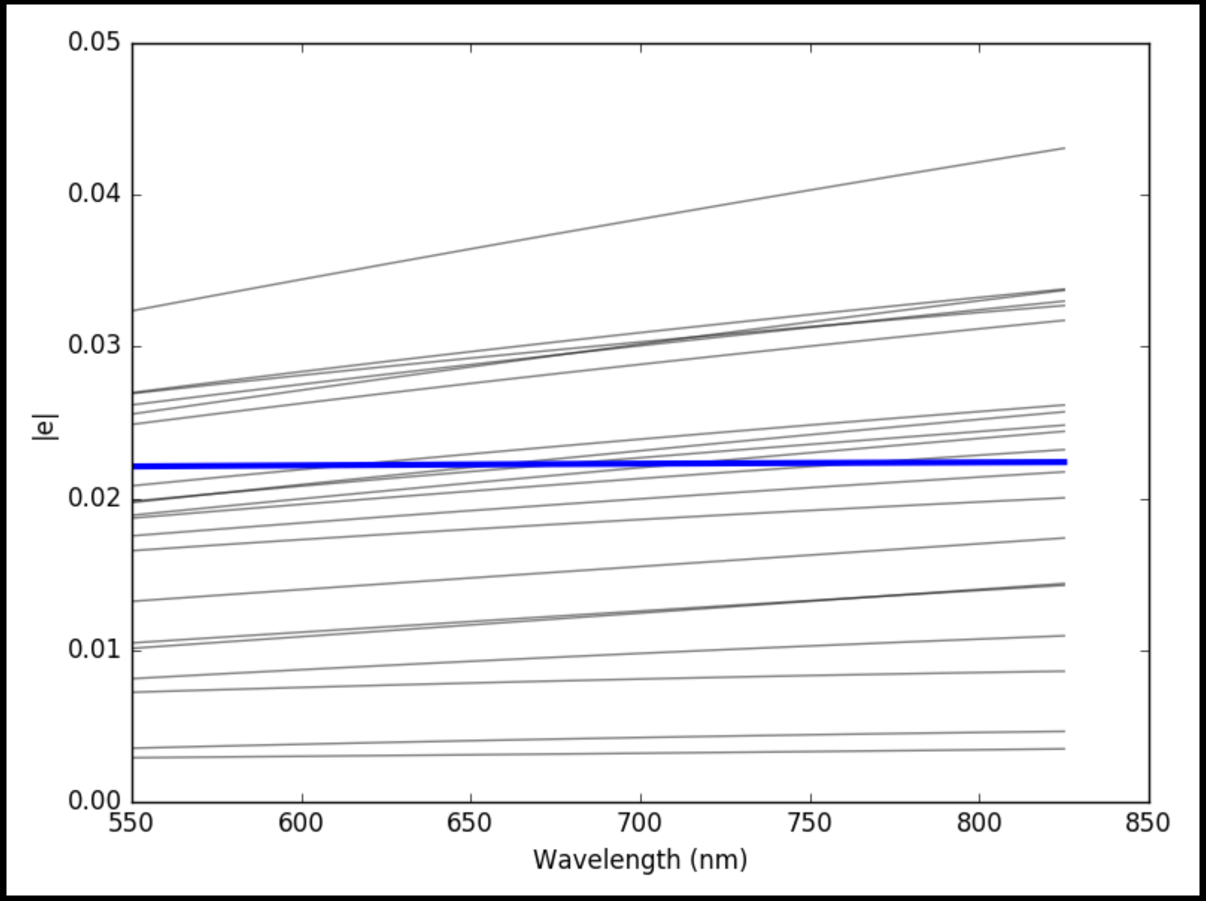




Chromaticity of atmospheric PSF?

6 layers with Jee+Tyson relative amplitudes,
r0 = 0.2 m, L0 = 25 m
20 atmosphere realizations





GalSim AtmosphericPSF questions for DESC DC1

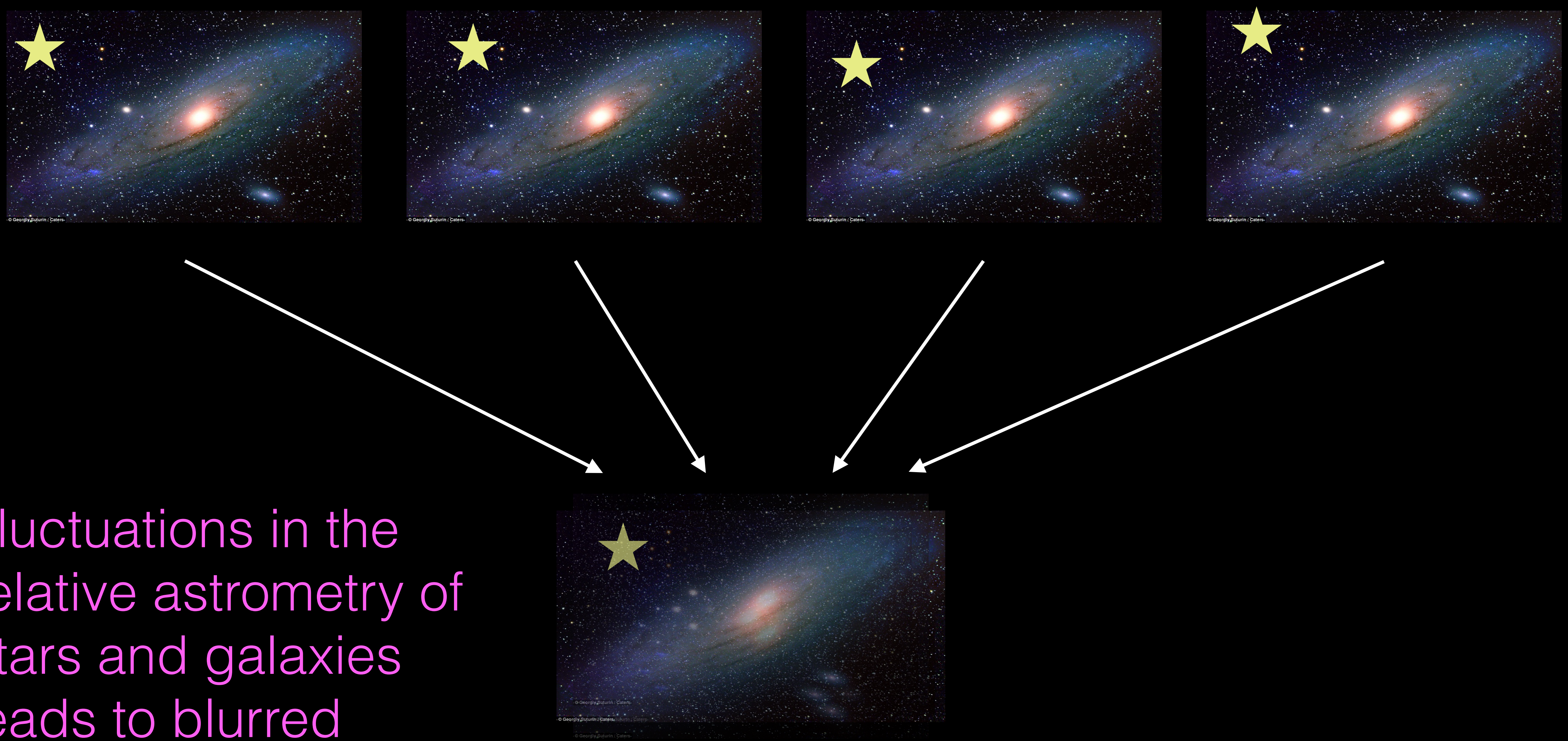
- DESC is planning to use GalSim implementation of AtmosphericPSF for data challenge 1. How do we decide …
- How many layers? What r0, L0, etc.? What resolution? What time step?
- Fresnel vs. Fraunhofer propagation?
- (How much data do we want? How much compute time do we have available?)

Questions

- How can we learn PSF chromaticity directly from data instead of relying on models?
- How can we accurately simulate the atmosphere?
- How can we use ancillary data to constrain the atmospheric PSF spatial variation?

Backup slides

Misregistration bias



Fluctuations in the relative astrometry of stars and galaxies leads to blurred stacked galaxy image.

Second moments of stacked galaxy image.

Assuming flux is the same in each epoch:

$$I_{\mu\nu}^{\mathrm{stack}} = I_{\mu\nu}^{\mathrm{single\,epoch}} + \underbrace{\langle(\mu-\bar{\mu})(\nu-\bar{\nu})\rangle_{\mathrm{epochs}}}$$

Since this term enters in exactly the same way as the PSF,

$$I_{\mu\nu}^{\mathrm{obs}} = I_{\mu\nu}^{\mathrm{gal}} + I_{\mu\nu}^{\mathrm{PSF}}$$

it can be treated as an error in the PSF:

$$\Delta I_{\mu\nu}^{\mathrm{PSF}} = \langle(\mu-\bar{\mu})(\nu-\bar{\nu})\rangle_{\mathrm{epochs}}$$

LSST requirement

Using formula on slide 2:

$$m_1 = m_2 = \frac{-\left(\Delta I_{xx}^{\mathrm{PSF}} + \Delta I_{yy}^{\mathrm{PSF}}\right)}{r_{\mathrm{gal}}^2}$$

LSST multiplicative bias requirement and galaxy size:

$$|m|_{\mathrm{max}} \sim 3 \times 10^{-3} \qquad \sqrt{r_{\mathrm{gal}}^2} \sim 0.''3$$

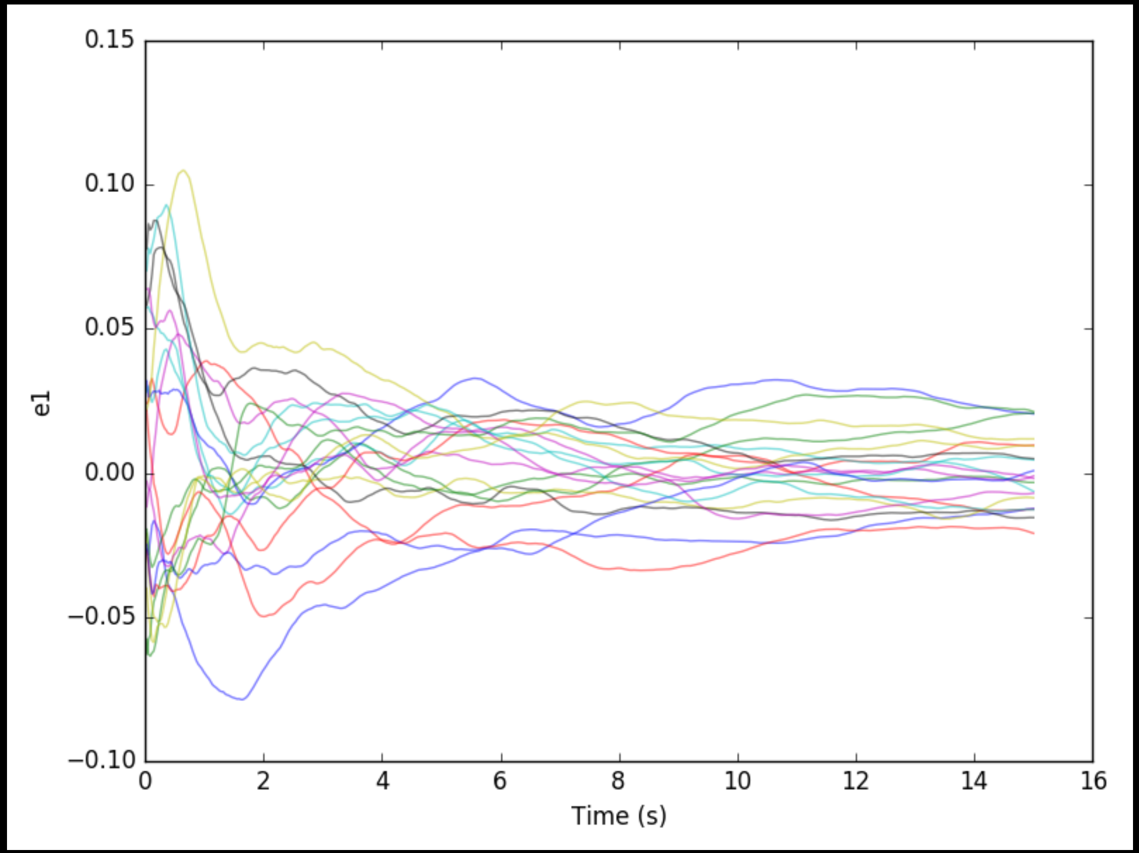
Implies the requirement:

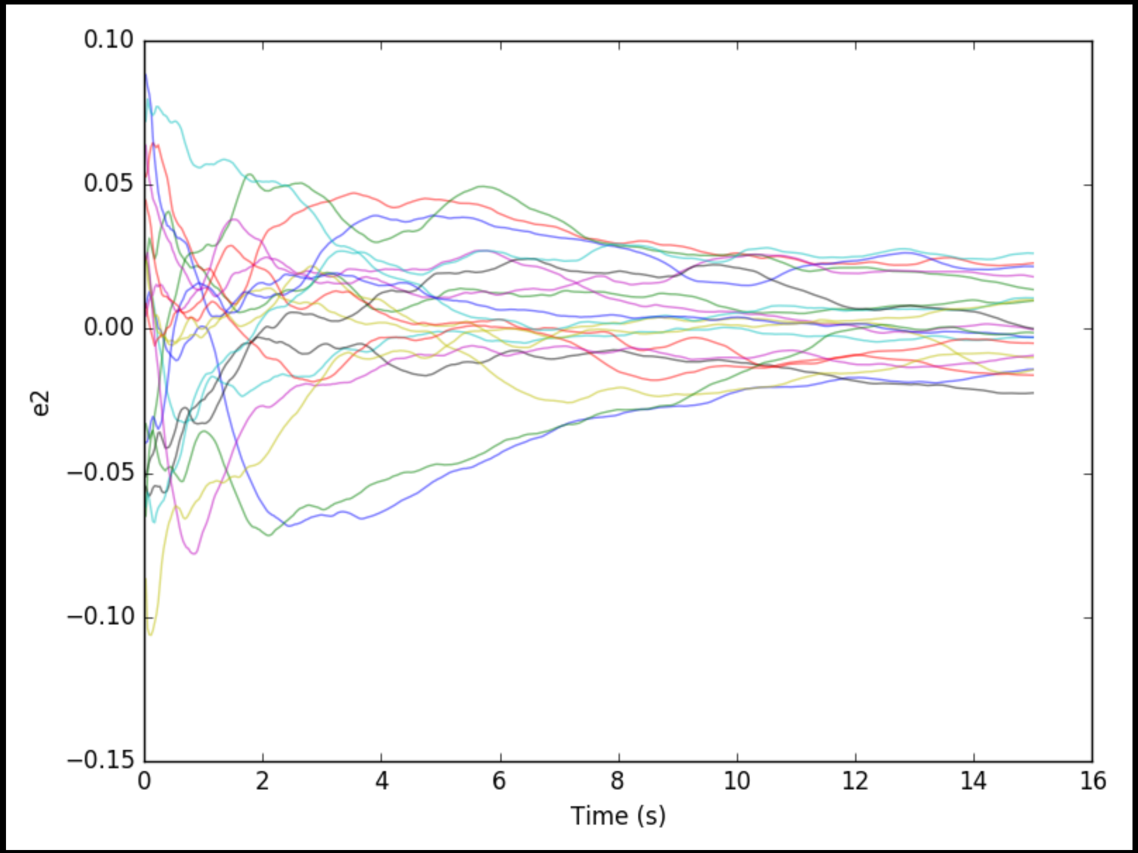
$$\left|\mathrm{Var}\left(x\right) + \mathrm{Var}\left(y\right)\right| < 2.7 \times 10^{-4} \mathrm{arcsec}^2$$

In terms of 2D RMS centroid shifts:

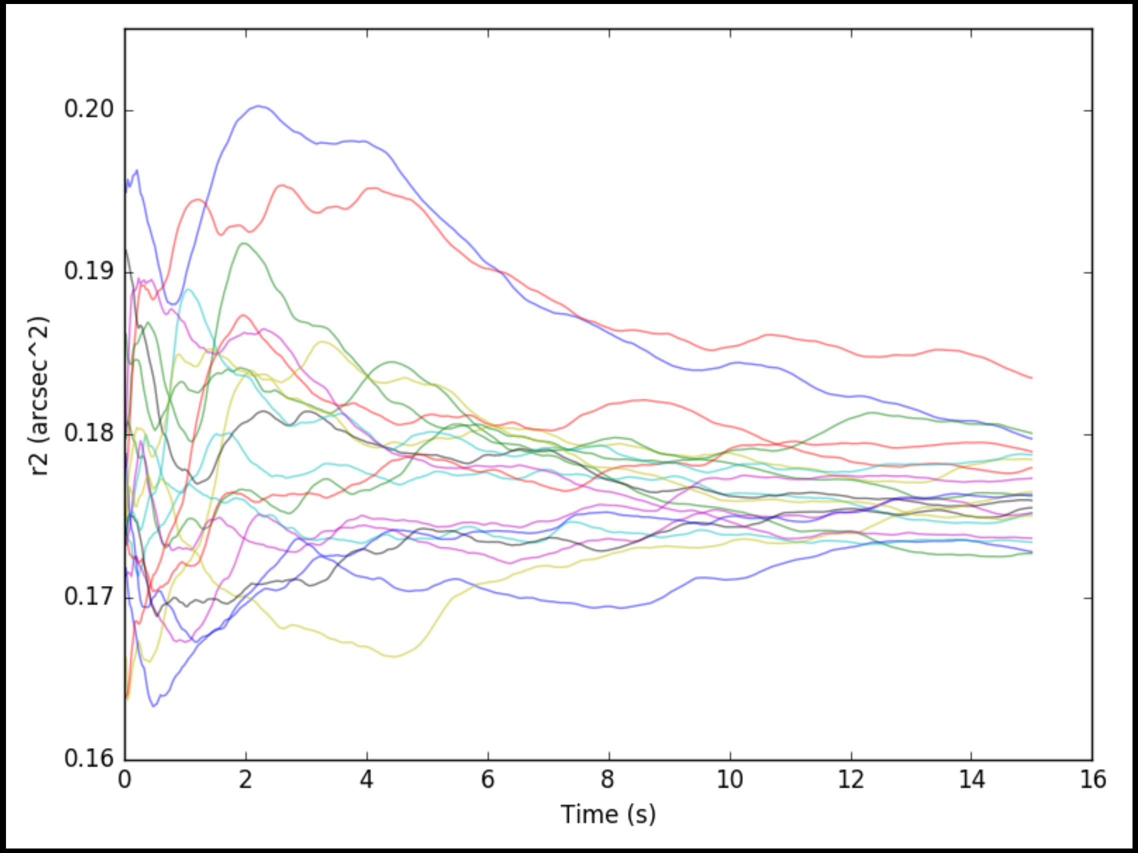
$$\sqrt{\left\langle \left(\vec{x}_i - \langle \vec{x} \rangle\right)^2 \right\rangle} < 16 \ \mathrm{mas}$$

PSF statistics vs time

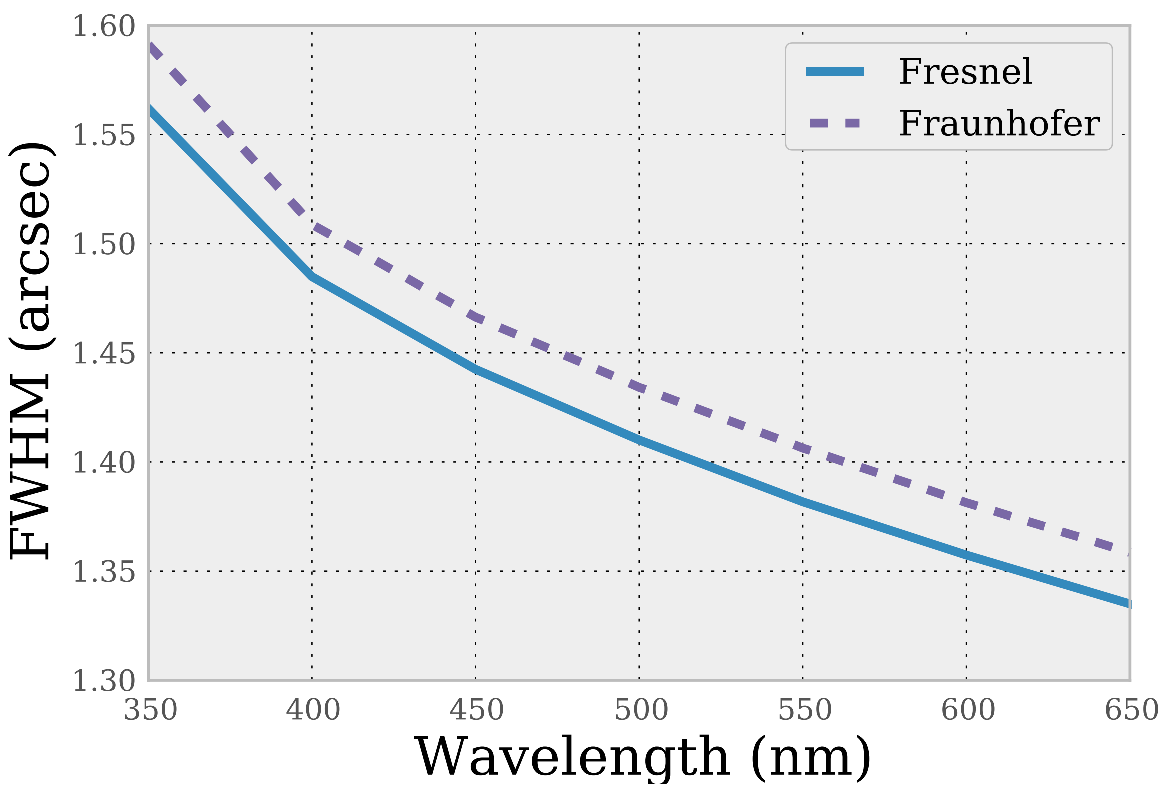


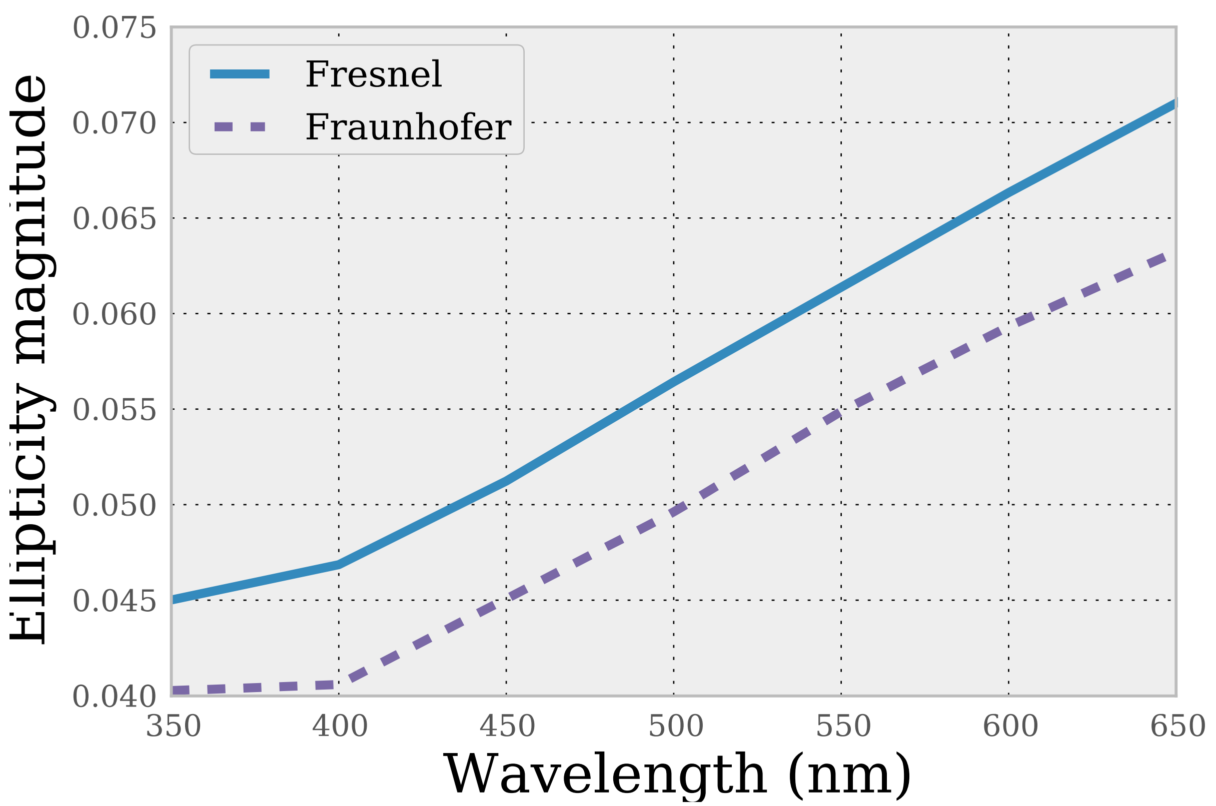


6 layers with Jee+Tyson relative amplitudes,
r0 = 0.2 m, L0 = infinity
20 atmosphere realizations



- 3 layer atmosphere with arbitrary r_0, wind velocity, no outer scale (!)
- Fresnel & Fraunhofer propagation using JPL Proper code
- 3 second integration





- Recover chromatic seeing
- Small difference between Fraunhofer and Fresnel (is this systematic?)
- Discover wavelength dependent ellipticity (!) (is this systematic?)